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HIGH GRADIENT CONDITIONING AND PERFORMANCE OF C-BAND β=0.5 PROTON NORMAL- CONDUCTING COPPER AND COPPER-SILVER RADIO-FREQUENCY ACCELERATING CAVITIES

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Abstract

This paper reports the results of high gradient testing of the two C-band (5.712 GHz) normal conducting β=0.5 accelerating cavities. The first cavity was made of copper and the second was made of copper-silver alloy with 0.085% silver concentration. The tests were conducted at the C-Band Engineering Research Facility of New Mexico (CERF-NM) located at Los Alamos National Laboratory. Both cavities achieved gradients more than 200 MeV/m and surface electric fields more than 300 MV/m. The breakdown rates were mapped as functions of peak surface fields. The gradients and peak surface fields observed in the copper-silver cavity were about 20% higher than those in the pure copper cavity with the same breakdown rate. It was concluded that the dominant breakdown mechanism in these cavities was not the pulse heating but the breakdown due to very high surface electric fields.

INTRODUCTION

Accelerators are essential for numerous applications in National Security (NNSA, DoD), medicine, discovery science and industry. These applications require accelerators with optimized cost of construction and operation, naturally calling for high-gradient acceleration. At Los Alamos National Laboratory (LANL), we started a new project with the major goal to use a multi-disciplinary approach that includes accelerator design, molecular dynamics simulations, and advanced manufacturing of metals to develop high-gradient, high-efficiency radio-frequency (RF) structures for both compact and facility-size accelerator systems [1]. Recently, we commissioned a high gradient test stand called C-band Engineering Research Facility of New Mexico (CERF-NM) that allows high gradient testing of C-band accelerating structures [2]. As a part of a collaboration with Stanford Linear Accelerator Center (SLAC) National Accelerator Laboratory, LANL has completed testing two high gradient C-band accelerator cavities designed for operation with the proton beam traveling at half of the speed of light (β=0.5). These cavities are part of research on a compact accelerator-based beam delivery system that will deliver protons to medical accelerators used for cancer therapy. The benefit of using protons over X-ray photons for cancer treatment is that the particle beams are more precise and target-oriented and cause less damage to neighboring healthy tissues compared to photon-based therapy. However, delivering hadron beams such as protons or light ions require accelerators on gantries that are larger and more expensive than conventional radiation therapy machines and gantries. The particle beams also have slow energy scanning rates, which increases the overall treatment time and makes the success of treatment susceptible to patient motion. In addition, the full potential of these machines is compromised because the slow methods used to adjust beam energies, also introduce additional energy and momentum spread in the beam. SLAC goal is to enable 3D scanning over a tumor volume of up to 4 liters in both transverse and longitudinal dimensions [3]. The cavities that are described in this paper are used to adjust the energy of the proton beam for longitudinal variation in dose deposition. They are designed for optimal operation with 150 MeV protons with a radial port for coupling power and no on-axis coupling. Each accelerating cell in the linac will be individually powered so that the phase can be adjusted for the beam energy and vary rapidly and dynamically. This allows the linac to maintain its efficiency whether accelerating or decelerating the beam within a range of at least 50 MV/m.

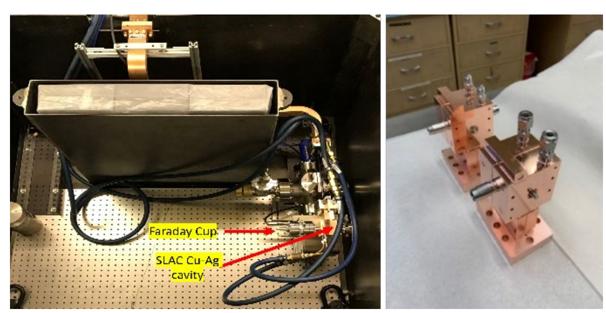

Figure 1: A photograph of the two β=0.5 accelerator cavities fabricated at SLAC (right). A photograph of the copper cavity installed on the test stand for high gradient testing (left)

HIGH GRADIENT TESTING SYSTEM (CERF-NM)

CERF-NM, is powered by a Canon klystron capable of producing peak power of 50MW with operating pulse length up to 1 μs at a maximum repetition rate of 200 Hz.

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The cavities under test are installed in a lead box to protect operators from X-rays generated by dark current. The photograph of the installation is shown in Fig. 1. The cavity is water-cooled continuously during testing. The klystron output power is split into two halves with a magic tee and then fed to the cavity through a directional coupler and WR187 waveguides. The waveguides were conditioned up to a maximum power of 30 MW, whereas the klystron was conditioned to full power 50 MW. During testing, the base pressure was 5×10^{-7} torr. Thermocouples were attached to the body of the cavity and RF windows to monitor temperature rise at the time of testing. There are two directional couplers and one Faraday cup for diagnostics purpose. The first directional coupler was placed immediately after the klystron and the other just before the cavity for measurements of incident and reflected powers. The Faraday cup was placed at the beam pipe after the structure to measure dark current which is indicative of vacuum breakdowns at the cavity being tested. All the data such as pulse count, breakdown pulse count, number of breakdowns, and real-time monitoring of signals are collected by a national instruments PXIE chassis that implemented in FPGA oscilloscope for real-time measurement. The control systems analysis code which is known as FEbreak was able to achieve a 95% pulse capture efficiency [4]. The details of the test stand, its capabilities are reported in [2].

TESTING OF SLAC BETA=0.5 ACCELERATOR CAVITIES

Table 1: Characteristics of the SLAC β=0.5 Cavities

	Cu	Cu-Ag
Frequency	5.71205 GHz	5.711325
Length	1.18 cm	1.18cm
Shunt impedance	77.78 MΩ/m	79.33 MΩ/m
E_a	$81.19\sqrt{P[MW]}$ MV/m	$82.81\sqrt{P[MW]}$ MV/m
E_p/E_a	2.26	2.26
$H_p * Z_0 / E_a$	1.25	1.25
Q_{ext}	9742	9805
$2*\tau$	269.75ns	272.04ns

We tested two cavities fabricated by SLAC. One cavity was made of a pure high conductivity copper, and the other one was made of a copper-silver alloy with 0.085% of silver. The photographs of the two cavities are shown in Figure 1 (right). The cavities were cold-tested and tuned to the frequency close to 5.712 GHz. Both cavities were tested at the pulse length of 700 ns and 1 μs. Copper cavity was also tested at the pulse length of 400 ns. We could not test copper-silver cavity at this pulse length due to limitation on reflected power of the Canon klystron. The repetition rate was kept at 100 Hz through the whole testing. The cold test and coupling results were reported in and the computed characteristics of the two cavities are shown in Table 1.

The testing of cavities proceeded as follows. We started with conditioning the cavity and waveguide components to the highest gradient and then conducted high gradient testing of the cavities and mapped breakdown probabilities. The schematic for this experimental procedure is shown in Fig. 2. We conditioned the cavities first with 100Hz rep rate and lowest power. Next, we raised power in 0.5MW increments and recorded number of breakdowns (BD) in an hour. We continued increasing power until we reached to a power level where the number of BDs in an hour was more than one hundred. At this power level, we counted BDs for several hours to ensure that the number of BD is consistently more than one hundred. When this happened, we recorded this power level, and this was set as maximum operational power level for that pulse length. The same process was repeated at longer pulse lengths.

After conditioning was complete for all pulse lengths, we proceeded with breakdown mapping. We started at the maximum operational power level and counted number of breakdowns for several hours in a row until we got consistent number of breakdowns for two contiguous hours. When we achieved consistent BDs for certain power level, we recorded it and moved to a lower power level by reducing input power by 0.5MW. A typical RF forward and reflected pulses from the cavity testing are shown in Fig. 3. Modelled input pulses using measured Q factors of the cavity are also shown for comparison. The shape of reflected pulses provided estimate of the coupling factor beta of the cavity which was found to be close to 0.92.

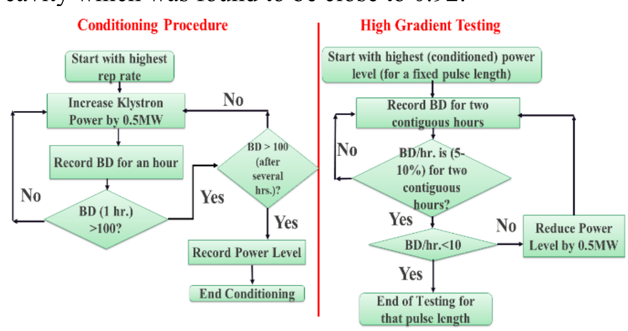

Figure 2: Conditioning and high gradient testing procedure for SLAC copper and copper silver cavities.

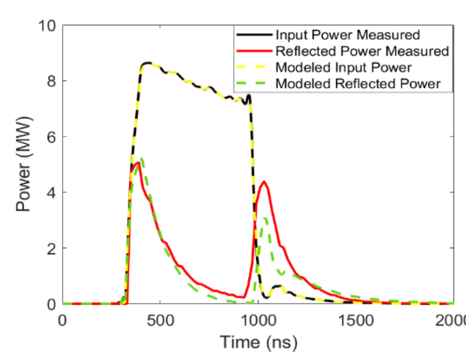

Figure 3: Typical measured 700 ns pulse shape for high gradient testing of SLAC copper and copper-silver cavity.

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We also modeled pulse shape from measured cold-tested S-parameters previously reported in [5]. The model shows reasonable agreement with measured pulses.

HIGH GRADEINT TESTING RESULTS

After collecting data using FEbreak [4], we processed the data with a routine developed in MATLAB. Using the forward and reflected pulse shapes, we calculated gradient, peak surface electric, and surface magnetic fields. We also computed breakdown rates for both copper and copper-silver cavities by calculating number of breakdowns per pulse length per meter. Breakdown rates were plotted as functions of peak surface electric and surface magnetic fields. The breakdown maps are shown in Fig. 4 and Fig. 5. Both copper and copper-silver cavities achieved peak surface electric fields higher than 300 MV/m and peak surface magnetic fields higher than 450 kA/m. The fields in the copper-sliver cavity were about 20-25% higher than in the pure copper cavity. We also observed pulse heating for both cavities, which is shown in Fig. 6.

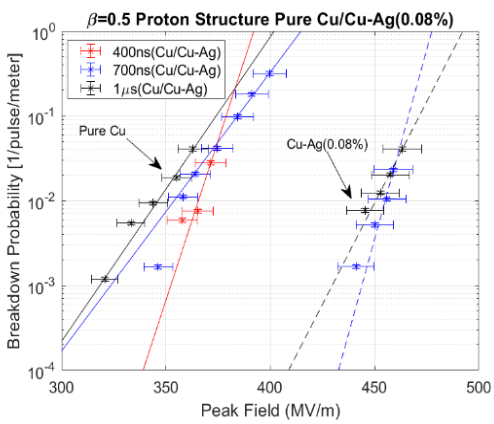

Figure 4: Breakdown probabilities in copper and copper-silver cavities plotted versus peak electric field.

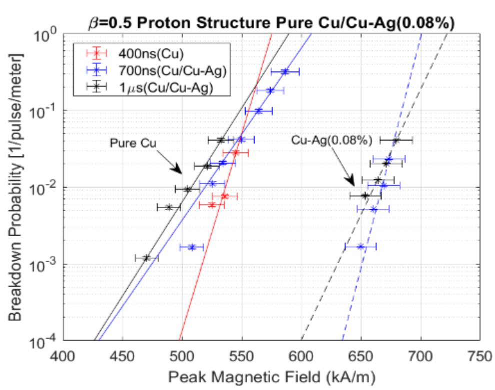

Figure 5: Breakdown probabilities in copper and copper silver cavities plotted versus peak magnetic field.

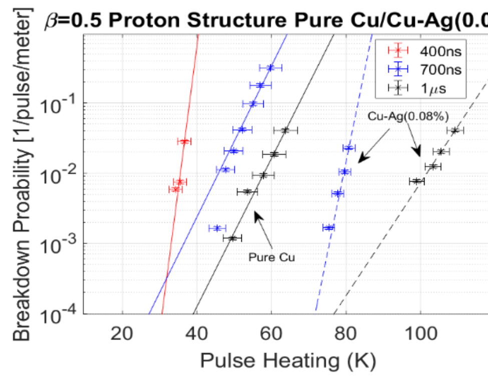

Figure 6: Breakdown rates as a function of peak pulse heating during the pulse.

CONCLUSION

In summary, we tested two SLAC β=0.5 cavities fabricated for proton beam delivery intended for radiation therapy. The cavities were tested at CERF-NM test stand at LANL. The testing was conducted at pulse lengths of 400 ns, 700 ns and 1 µs for pulse repetition rate of 100Hz. Using the collected breakdown data from high gradient testing of the cavities, we concluded that copper-sliver structure supported 20% higher peak fields than pure copper. Both cavities achieved peak surface electric fields greater than 300MV/m. Although we observed pulse heating for both these cavities, it was determined that there are other factors such as geometric and material properties that contributed to breakdown rates for each pulse length.

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